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Portland District

Willamette Basin Flow-Frequency Study

Farm between Salem and Wheatland during December 1964 flood
(Portland District Archives, picture W4-11)

January 2024

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EXECUTIVE SUMMARY

This study assesses the likelihood of flood flows at areas downstream of USACE dams in the Willamette Valley. The study includes both natural conditions with no reservoirs present (unregulated), as well as the existing condition with all reservoirs (regulated). These two conditions help quantify the flood risk management (FRM) benefits of the Willamette Valley Project (WVP). This information is critical for communicating flood risk to communities for floodplain management and emergency action planning. The probability of flooding is quantified by developing flow-frequency curves throughout the basin. Flow-frequency curves show the chance of river flows rising above a level of interest in any given year, known as annual exceedance probability (AEP). This study is focused on floods, not low flow conditions.

The study reflects current basin and climate conditions. Flood risk is not a constant through time—it changes as a result of both natural and human-induced causes. While flood risk has changed in the past and will likely continue to change in the future, this report represents a best estimate of current-day conditions. A summary of climate change effects is included in this study.

The final adopted unregulated results are in Appendix B, and the final adopted regulated results are in Appendix G. General conclusions from this report are listed below:

- **The uncertainty in the unregulated frequency estimates is dominated by the limited period of record of flood events.** Hydrologic uncertainty from a limited period of record was the largest variable impacting the certainty of results. Since observed data is available only for around 150 years, there is relatively low confidence in estimates of extreme floods.
- **Reservoir regulation has significantly reduced the chance of flooding**. This is not a new finding, but this study revisited the quantitative analysis. It confirmed that the upstream system of reservoirs is effective in reducing even very large floods. For example, the system of reservoirs has lowered the likelihood of reaching major flood stage at Salem in any given year from approximately 33% (1 in 3) to 7% (1 in 14). Even at an extreme 0.1% AEP (1000-year) flow, the reservoirs still provide an appreciable reduction in peak flows at all locations.
- **Changes in reservoir operations have not increased flood risk**. While there have been changes to reservoir operations policies for ecosystem purposes and Endangered Species Act compliance, these operational changes have not increased flood risk. This outcome was expected since the operational changes were formulated to avoid flood risk increases. The study approach easily allows future proposed operational changes to be evaluated and compared.
- **Damaging floods can occur many different ways.** Damaging floods can be produced by different mechanisms, such as a single extremely large winter storm when pool levels are low, a series of back-to-back events, or a smaller storm that occurs in the spring when reservoir levels are high. The dominant flooding mechanism varied by location and flood level. The recent April 2019 flood was a reminder that damaging floods are not limited to winter months.

- **The uncertainty in the regulated frequency estimates is a mix of model error and hydrologic uncertainty.** At common events, like the 50% AEP (2-year), the uncertainty in the estimate is dominated by model error, reflecting the inability of models to replicate real-time decisions. At rare events, like the 0.1% AEP (1000-year), the model error term is largely overwhelmed by hydrologic uncertainty from a limited period of record of observations. The probability of inflow events at these high levels is very uncertain.
- **The regulated flow-frequency curves from this study generally are lower than previous studies**. At most locations, the 1% AEP (100-year) event flow is lower in the current study than in previous FEMA effective studies. There are some exceptions, most notably at Blue River, Foster, and Salem. It is challenging to attribute the cause of these differences due to sparse documentation of the previous studies. The previous studies may have been more conservative, leading to higher estimates.

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FIGURES

APPENDICES

VERSION HISTORY

Number	Description	Date
1.0	ATR completed on unregulated analysis	December 2022
2.0	ATR completed on complete report	September 2023

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ACRONYMS

Acronym	Description
AEP	Annual Exceedance Probability
AR	Atmospheric River
ATR	Agency Technical Review
cfs	Cubic feet per second
DQC	District Quality Control
ECB	Engineering Construction Bulletin
EIS	Environmental Impact Statement
EM	Engineering Manual
EMA	Expected Moment Algorithm
ER	Engineering Regulation
ERL	Equivalent Record Length
FIM	Flood Inundation Mapping
FIS	Flood Insurance Study
FRA	Flood Risk Assessment
FRM	Flood Risk Management
HEC	Hydrologic Engineering Center
HEC-HMS	HEC Hydrologic Modeling System
HEC-RAS	HEC River Analysis System
HEC-ResSim	HEC Reservoir System Simulation
HEC-SSP	HEC Statistical Software Package
HEC-WAT	HEC Watershed Analysis Tool
kcfs	Thousand cubic feet per second
LPIII	Log Pearson III
Maf	Million acre-feet
NAVD88	North American Vertical Datum of 1988
NFIP	National Flood Insurance Program
NGVD29	National Geodetic Vertical Datum of 1929
NOAA	National Oceanic and Atmospheric Administration
PDT	Project Delivery Team
POR	Period of Record
QA	Quality Assurance
QC	Quality Control
RM	River Mile
RS	River Station
SLC	Sea Level Change
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
WVP	Willamette Valley Project

SECTION 1 - INTRODUCTION

1.1 PURPOSE

This study assesses the likelihood of flood flows at areas downstream of USACE dams in the Willamette Valley. The study includes both natural conditions with no reservoirs present (unregulated), as well as the existing condition with all reservoirs (regulated). These two conditions help quantify the flood risk management (FRM) benefits of the Willamette Valley Project (WVP). This information is critical for communicating flood risk to communities for floodplain management and emergency action planning. The probability of flooding is quantified by developing flow-frequency curves throughout the basin. Flow-frequency curves show the chance of river flows rising above a level of interest in any given year, known as annual exceedance probability (AEP). This study is focused on floods, not low flow conditions.

This study establishes a new benchmark of flood risk understanding, but it also allows for additional evaluations. The methods in this study allow Portland District staff to evaluate the flood risk effects (either positive or negative) of proposed operational changes. In addition, this study can be used in wildfire assessments as the “pre-fire” condition to analyze the effects of fire on flood probability. As flood inundation mapping (FIM) becomes more of a focus, this study will allow probabilities to be tied to the flood maps at various river stages. In addition, future Flood Insurance Study (FIS) updates could use this study for FEMA floodplain management applications.

In 2022, a stage-frequency study was completed for the Lower Columbia River and the Lower Willamette River downstream of Willamette Falls (USACE 2022a). The flow-frequency analysis from the current study would allow for hydraulic analysis to be performed to establish stage-frequency curves in the areas upstream of Willamette Falls. If that work is undertaken, stage-frequency results would be available from the Pacific Ocean upstream to the USACE dams in the Willamette Valley.

1.2 REFERENCE STUDIES

Basin-wide flow-frequency analyses that include the effects of a large system of reservoirs are usually very complex studies updated very infrequently. However, a few recent studies in other areas served as useful references. Many of the methods in the Central Valley Hydrology Study (USACE 2015) were applicable, since the Sierra Nevada mountains in California are somewhat hydrologically similar to the Cascade Range in the Willamette Basin. The Lower Columbia River Basin Peak Stage-Frequency Report (USACE 2022a) included the Willamette River as an input to the hydraulic model of the Lower Columbia River Basin. Many of the techniques used in that study were used here as well. While many studies have been performed for the Columbia River Basin in the last decade, most work related to flood risk has been centered around the Lower Columbia River. A comprehensive basin-wide flow-frequency assessment for regulated conditions has not been performed recently in the Willamette Basin.

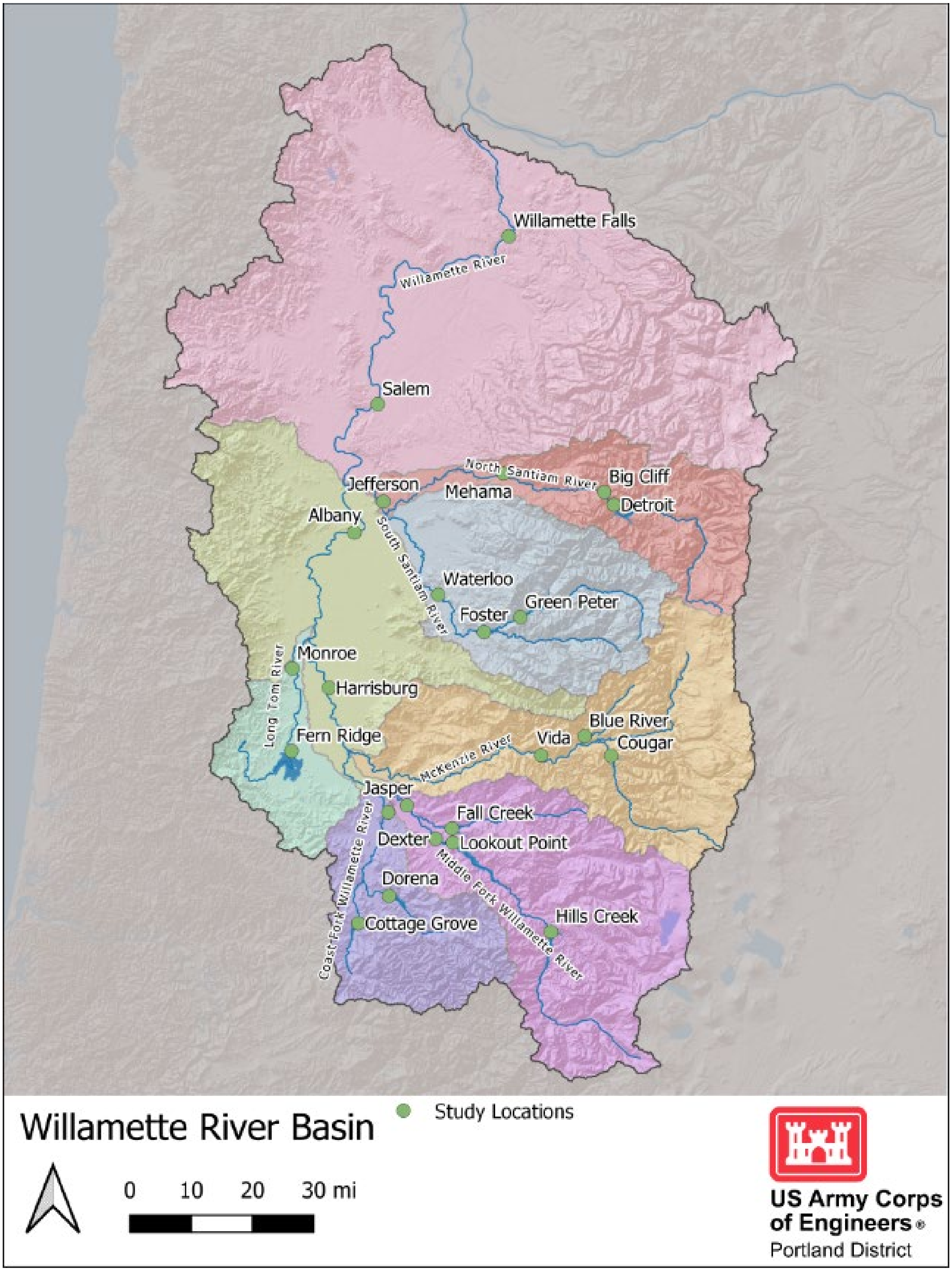
1.3 STUDY AREA

The study area is the Willamette River Basin upstream of Willamette Falls at Oregon City. The study locations are 24 discrete points in the basin, shown in Table 1-1 and Figure 1-1. The study locations are significantly affected by upstream reservoir regulation. These locations have long-term gage records. While unregulated tributaries were important as flow inputs to this work, frequency analysis at those sites was not a primary focus of the study. No study locations are on the Tualatin River, which is the only other river in the Willamette Basin affected by upstream flood reservoir regulation. Scoggins Dam on Scoggins Creek, a tributary to the Tualatin River, is operated by the Bureau of Reclamation, but flood storage is authorized under Section 7 of the Flood Control Act of 1944. While Scoggins Dam is important for studies of the Tualatin River, it has an insignificant effect on flood flows in the mainstem Willamette River (USACE 2018).

Table 1-1. Study locations

Reservoirs	Other Gage Locations
Hills Creek	Jasper
Lookout Point	Goshen
Dexter	Vida
Fall Creek	Harrisburg
Cottage Grove	Monroe
Dorena	Albany
Cougar	Waterloo
Blue River	Mehama
Fern Ridge	Jefferson
Green Peter	Salem
Foster	Willamette Falls (Oregon City)
Detroit	
Big Cliff	

Figure 1-1. Study location map



1.4 KEY ASSUMPTIONS

- **Floods are Independent**. When analyzing annual maximum peaks, flood events from all years are considered independent. In other words, the fact that a large flood occurred in one year has no bearing on the chance of a large flood in the next year. This assumption is reasonable in the Willamette Basin, where the predominant flood season is generally November-April. Reservoirs do not have carryover flood storage from year to year—they reach their minimum flood pools every year in October or November, depending on the project.
- **Floods are Identically Distributed/Climate stationarity**. A principal assumption in a typical flood frequency statistical analysis is that the time series data are stationary. In other words, the statistical properties of the forcing meteorology are unchanging with time. This assumption means that observed past flood events are indicative of probability distribution of future floods. Climate change effects for future conditions are evaluated separately in Section 7.
- **Use of Annual Maxima Data**. Annual maxima data was used as the basis for the frequency analysis, rather than a partial-duration analysis, also known as peaks-over-threshold. Since the period of record (POR) of data is quite long (over 100 years in most cases), the difference between partial duration and annual maxima analyses is expected to be negligible for the upper extremes of the frequency curve when using graphical methods. If a statistical distribution such as Generalized Pareto is fit to the data, the partial-duration analysis would produce different estimates at rare AEP where the distributions are extrapolated.
- **Evaporation/Irrigation**: Major floods in the Willamette Basin occur from November to April when evaporation and irrigation are minimal. Evaporation and irrigation were assumed negligible in this study since it is focused on FRM and not conservation season operations.
- **Diversion canals**: Major diversion canals for hydropower exist at Leaburg and Walterville on the McKenzie. Past operations have shown that these canals are typically shut off during flood events. Canal flow data was retrieved and used when calibrating past flood events, but flow frequency analysis assumed that these canals do not provide a FRM benefit by diverting flow.
- **Land Use**: The rainfall-runoff characteristics of the basins are assumed homogeneous and largely unchanged over the POR for all gages. While forestry practices and urbanization have changed slightly through time, these changes are not expected to produce a noticeably different flood response at the large basin scales considered in this study.
- **Flow-based**: Probabilities of flooding in this study are largely inferred from flow values. Precipitation-frequency relationships paired with rainfall-runoff modeling were not used for this study, as discussed later. Rainfall-runoff modeling was used to produce synthetic floods larger than those observed to-date. However, the probability of flooding was entirely based on flow records.

- **Reservoir Release Capacity**. Full reservoir release capacity was assumed available in this analysis. This includes releases through powerhouses, regulating outlets, and spillways. Probable Maximum Flood (PMF) studies of extreme conditions typically assume that powerhouses are not available for releases (USACE 1991), but the flows considered for this study do not approach the PMF.
- **Endangered Species Act (ESA) operations**. The Willamette Valley Project has implemented many operational changes in recent years as a response to Endangered Species Act responsibilities, largely from the 2008 Biological Opinion (BiOp). USACE is preparing a new EIS and the National Marine Fisheries Service and U.S. Fish and Wildlife Service will issue new Biological Opinions that may further revise operations. The Biological Opinions are expected by the end of 2024 and the EIS is expected to be completed in early 2025. These Biological Opinion operational changes were formulated to avoid increasing flood risk (USACE 2022c). The study assumed operations conformed to EM 1110-2-1415, which states that operations for project purposes other than FRM may provide incidental storage space, but the effect of this space on FRM should be estimated very conservatively. The operations used in this study are termed FRM Baseline and detailed in Appendix E.
- **Interim risk reduction measures (IRRMs).** Various IRRMs are currently in place in the Willamette Basin. These IRRMs range from summer pool restrictions for seismic risk reduction to spillway gate tracking requirements to reduce trunnion pin friction. This study does not include IRRMs in the reservoir operation modeling. In general, the IRRMs have a very minor effect on flood risk aside from dam breaching, which is beyond the scope of this study. It is assumed that construction will take place in the coming years that will allow these IRRMs to be lifted.
- **Forecasts**: In real-time, operators often look at streamflow forecasts to help guide reservoir operations. Water control manuals for the projects do not assume that any forecasts are available, and instead provide direction using water on the ground. This analysis assumes operations follow guidance in water control manuals, so forecasting is not included in this analysis. A forecast-informed reservoir operations (FIRO) study is starting in the Willamette, but it is a few years away from completion. If FIRO is incorporated into water control manuals in the future, this flow-frequency study could be updated to use that forecast information.

1.5 STUDY LIMITATIONS

The end products of this study are annual flood flow-frequency curves with the following limitations:

1. **Probability Range**: Results are provided for AEP between 50% (2-year) and 0.1% (1,000-year). While flood-frequency estimates at the 0.1% AEP event have large uncertainty, the frequency curves extend to this level to better assess the convergence between regulated and unregulated flows.
2. **Flooding mechanisms**: Frequency curves are only provided for the atmospheric river flooding mechanism, which generates annual maximum flows throughout the Willamette, typically between November and March. Other flooding mechanisms were not considered, such as snowmelt, summer thunderstorms, and upstream dam failure. Discussion on mixed populations is provided in Appendix B.
3. **Reservoir regulation**: Both unregulated and regulated curves are provided.
4. **Duration**: Unregulated analysis includes instantaneous peak flows and flood volume durations between 1-day and 15-day. Regulated analysis includes instantaneous peak only.
5. **Uncertainty**: Uncertainty bounds are explicitly defined for the 90% confidence interval (5 and 95% confidence limits).

SECTION 2 - BACKGROUND

2.1 WATERSHED DESCRIPTION

The Willamette River Basin is in northwest Oregon, in the greater Cascades Geological Province, which extends from British Columbia to northern California. The river has a watershed area of 11,478 square miles, with a length of about 180 miles and roughly 100 miles wide. The runoff of the watershed fluctuates dramatically from heavy precipitation in the winter months, snowmelt in the spring months, and relatively rain-free summers. The river bed is approximately 450 feet above sea level at the southern end of the valley and ten feet above sea level at its confluence with the Columbia River.

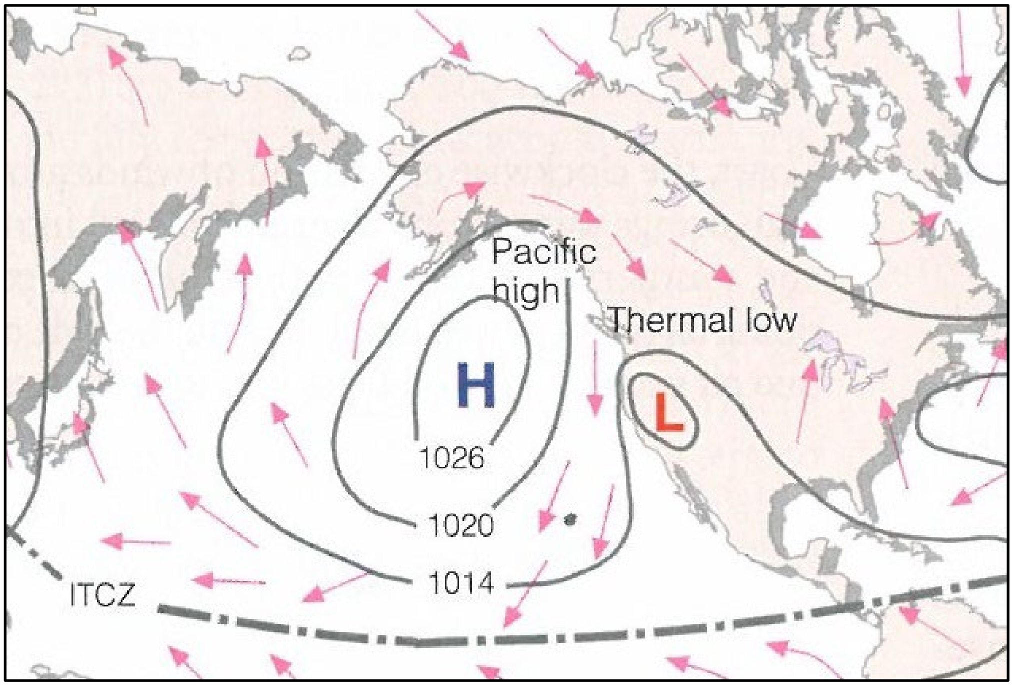
The Willamette River Basin is comprised of the valley area with an average elevation of about 200 feet North American Vertical Datum of 1988 (NAVD88), the Coastal Range along the west side ranging in elevation from approximately 1,030 to 5,000 feet, and the Cascades Mountain Range on the east side ranging in elevation from approximately 7,500 to 10,500 feet. The topography of the basin influences the temperature and precipitation patterns that occur in the watershed. The regional climate is shaped by maritime influences: southward seasonal ocean currents and prevailing eastward winds in the wet season and southward in the dry season. Warm, moist air blowing in from the southwest produces heavy precipitation in the late fall, winter, and early spring months in the Coast Range, producing intense seasonal rains with light, transitory snowfall at the higher elevations. The Cascade Range to the east has an equally significant seasonal precipitation. The Cascades also provide a buffer from continental climatic influences, creating a unique blend of topographic relationships that shape the regional climate.

The Willamette River Basin is comprised of various land use coverage with predominate coverage being evergreen forest (51.3%), hay/pasture/cultivated crops (15.2%) and shrub/scrub (11.7%), based on the National Land Cover Database (USGS 2006). Development is in localized areas with about 7.3% of the basin being classified as developed. The watershed upstream of each dam being analyzed has negligible urban development.

2.2 METEOROLOGY

The climate of the Pacific Northwest region has distinct wet and dry seasons with most of the annual rainfall occurring between November and March and dry conditions between May and August. On the valley floor, the summer high temperatures regularly exceed 90°F while winter lows are regularly below freezing. The contrast between warm, dry summers and cool, wet winters occurs because of a distinct weather pattern shift related to two features: (1) the semi-permanent area of high pressure over the eastern Pacific (Pacific High) and (2) the Gulf of Alaska low pressure circulation (Aleutian Low). In the late spring and early summer, the Pacific High expands and dominates the weather in the region (Figure 2-1), creating a subsiding air mass where moisture evaporates, and air temperatures become warmer. The area of high-pressure blocks and weakens storms moving into the region from the west or northwest. This pattern is further enhanced by the relatively cool ocean sea surface temperatures along the West Coast that serve to stabilize the lower levels of the atmosphere.

Figure 2-1. Average position of Pacific High in July (Ahren 2005)



The pattern described above changes beginning in September as the difference in temperatures between the Equatorial Regions and the Polar Regions increases. This temperature difference creates large air density differences in the mid-latitudes that strengthen the polar jet stream. As a result, the Aleutian Low strengthens, and the Pacific High weakens (Figure 2-2). A circulation of air around these two pressure centers over the ocean brings prevailing southwesterly and westerly atmospheric flow into the Pacific Northwest. Air inflowing to the continent is laden with moisture after travelling long distances through the marine boundary layer. Condensation occurs as the air moves inland over the cooler land and rises along the windward slopes of the mountains. The result is a wet season that reaches a peak in winter, and then gradually decreases in the spring.

The Pacific Northwest region is influenced by strong areas of low pressure (mid-latitude cyclones) moving in from the Pacific Ocean. These storms often bring with them high levels of moisture from tropical and subtropical sources and active storm dynamics. The combination of enhanced lift and moisture often lead to widespread heavy rainfall that may last three or more days. When these storms can obtain high levels of moisture, supplied by moisture-rich tropical and subtropical regions of the Pacific Ocean, extreme rainfalls can occur. This type of storm is an atmospheric river, or sometimes referred to as a “Pineapple Express” (Figure 2-3). As the storms approach the Willamette River Basin, the precipitation is further enhanced by orographic processes as the storm moves onshore and is forced to rise over the slopes of the Coastal Range and the west slopes of the Cascades. These wintertime synoptic storms, most common from

November through March, cover large areas and produce heavy rains over relatively long periods.

Figure 2-2. Average position of Pacific High in January (Ahren 2005)

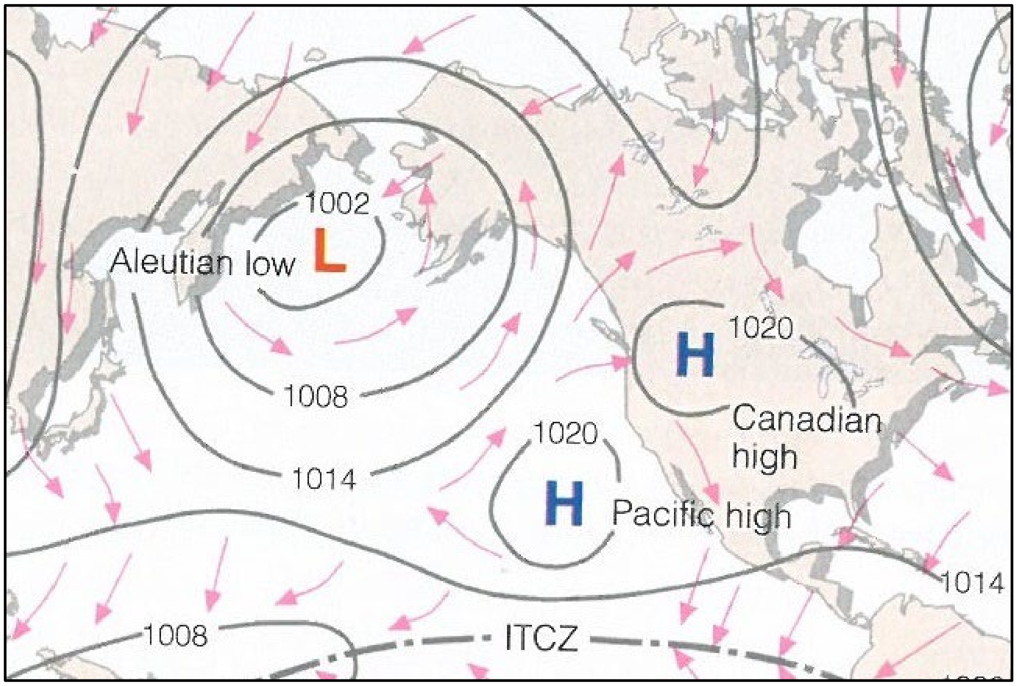
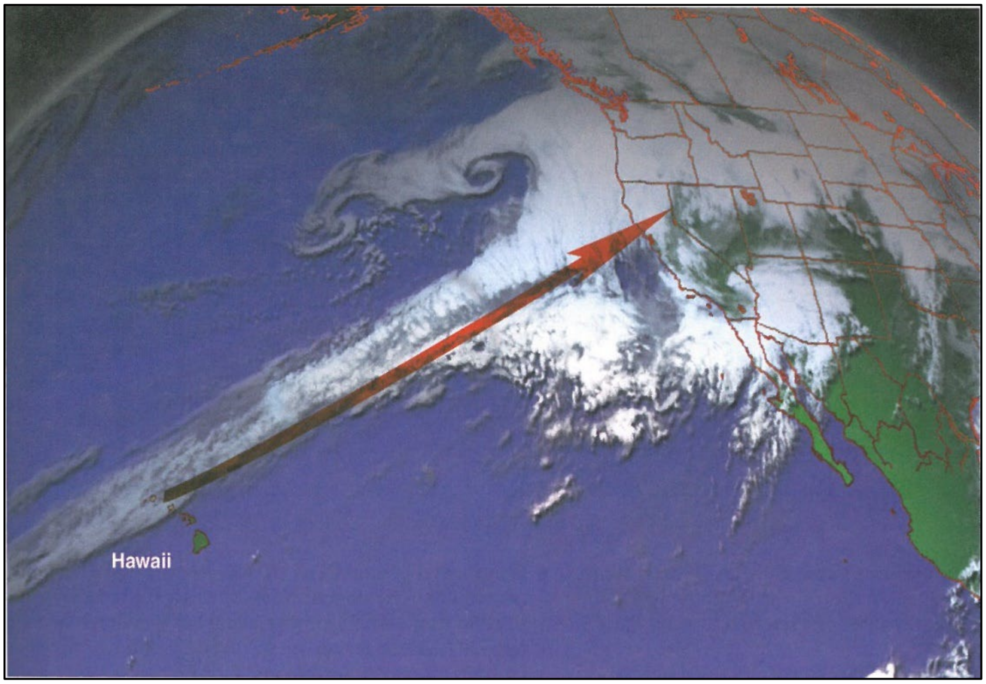


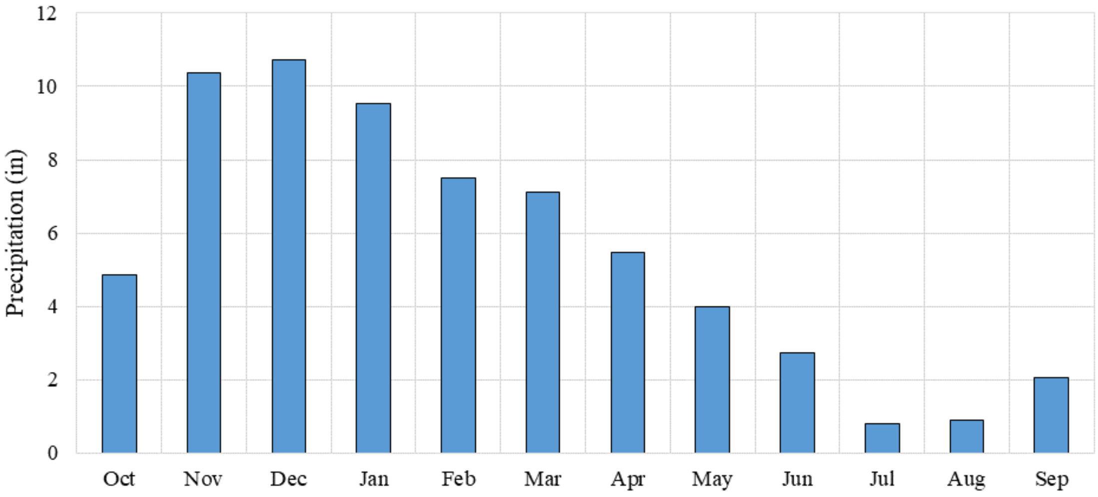
Figure 2-3. Atmospheric River (aka "Pineapple Express") type storm (Ahren, 2005)



2.3 PRECIPITATION

The climate in the basin is characterized by wet, cold winters and relatively dry, warm summers. In the higher elevations of the basin, average winter temperatures are generally near freezing, and snow often accumulates to great depths during the cold, wet winter months. The Parameters-Elevation Regressions on Independent Slopes Model (PRISM) at Oregon State University compiled raster datasets of monthly average precipitation and temperature data across the nation from 1981-2010 (PRISM Climate Group 2020). According to the PRISM dataset, the normal annual precipitation (NAP) in the basin varies from 38 to 147 inches. Approximately 2/3 of the annual precipitation occurs in the period from November through March (Figure 2-4). The average annual precipitation accumulation for the basin is 66 inches.

Figure 2-4. Monthly average precipitation accumulation for the Willamette Basin



The proportion of annual precipitation falling as snow varies greatly with elevation in the Willamette River Basin. Below 1,000 feet, snow typically falls for only a couple of days per year. Above 3,500 feet, snow generally begins accumulating in November and the snowpack usually lasts until late May or early June. Snowpack is generally transient between 1,000 and 3,500 feet, with snowpack depth and duration increasing with higher elevations. In many years, a snowpack may exist for several months at elevations above roughly 2,500 ft, but at elevations closer to 1,000 ft, snow generally persists less than a week or two (Harr 1981).

2.4 FLOOD HYDROLOGY

The fields of meteorology, hydrology, and river hydraulics all affect river levels in the Willamette Basin. Meteorology generally refers to weather events and associated conditions in the atmosphere, such as precipitation and temperature. Hydrology translates these atmospheric conditions into river flows by applying land surface processes like snowmelt, infiltration, runoff, and others. Hydrology also includes statistical analysis of flood flows. River hydraulics then translates input river flows into water surface elevations (stage). In general, when the term “hydrology” is used in this study, it generally refers to the collection of processes that result in river flows that generate high water levels in the Willamette Basin. Since the meteorologic and hydrologic processes are tightly tied together and this study does not always explicitly model meteorologic conditions, a more general use of the term “hydrology” is used that includes meteorologic processes. River hydraulics are not directly modeled in this study, but hydrologic routing techniques are used to incorporate attenuation and lag effects on flood flows as they move downstream.

Large winter rainfall events in the Pacific Northwest are caused by atmospheric rivers (ARs), which are enhanced water vapor plumes transporting large volumes of tropical moisture to extratropical locations. These storms normally occur during the period November through March and typically last three to five days, but they deliver a large amount of rain often augmented by low elevation snowmelt over their relatively short duration. They can sometimes generate a large snowmelt component due in part to relatively high temperatures. All significant flood flow events in the winter are sourced from atmospheric rivers, as evidenced by conversations with reservoir regulators and forecasters, review of post-flood reports, and other academic papers (Harr 1981, USACE 1966, USACE 1997, Barth et al. 2017, Corringham et al. 2019). Other mechanisms of precipitation in the winter do not produce significant flood flows. For more discussion on other potential flooding mechanisms considered, refer to Appendix B. Storm events in the spring are significantly less intense than winter storms, but storms during the months of April and May can accelerate snowmelt and cause flooding.

The largest flood event recorded at the Willamette River at Salem stream gage occurred in December 1861. The February 1890 flood was the second largest flood before the first flood storage dam was completed in 1940. Very little quantitative information is available for the floods of 1861 and 1890, except that obtained at mainstem gaging stations (USGS 1971). If no reservoirs were present, the December 1964 storm would have been the second largest event (USACE 1997). The February 1996 is the flood of record for the period after all upstream dams had been completed in 1969. The following paragraphs give summaries of the floods from existing literature.

A summary of the 1861 flood is as follows (USGS 1947): “The greatest flood known, that in December 1861, came soon after founding by white men of the first settlements and has not left many traces. A report in 1890 by the Chief Signal Officer, United States, Signal Service, on "The Climate of Oregon and Washington Territory," gave the following on the 1861 flood: "The November temperature was below normal during most of the month, with an excess of cloudiness which made it seem colder." At Fort Hoskins, in the central part of the basin, rainfall for November and December 1861 was 18.10 and 12.09 inches, respectively. This is 225 percent of normal for November and 140 percent for December. The above-normal precipitation combined with below-normal temperatures caused the accumulation of large quantities of snow in the mountains and produced conditions favorable for large direct runoff. The flood-producing storm, continuing from the last few days of November into the first days of December, passed over the Willamette Valley, bringing warm south winds and heavy rainfall. No daily values of rainfall are available, but the Oregon City Argus of December 14, 1861, stated "November's long and rather cold rain was succeeded during the closing days of the month by a warm, humid state of the air rain falling in copious showers almost without intermission." The rain and melting snow produced a discharge of 500,000 second-feet and a stage of 39 feet at Salem, 19 feet above flood stage. The direct runoff from this storm has been estimated to be 13 inches over the basin above Salem. More than 350,000 acres of land were inundated by this flood. Two towns were washed away, and every town along the river was in part submerged."

Less has been written about the 1890 flood, but it appeared similar in nature to the 1861 event. A summary of the 1890 flood is as follows (USGS 1947): "Because the second largest flood known, that of January and February 1890, occurred during a break in the gage-height record at Albany, there is no record of daily discharge. The maximum gage height taken from high-water marks at Albany was 33.9 feet, discharge 291,000 second-feet, and that at Salem, gage height 37.1 feet, discharge 450,000 second-feet. From records of the United States Signal Service for eight stations in the Willamette Valley, the average rainfall in the period January 26 to February 3, was 12.4 inches, probably considerably less than the average for the basin because only one of the eight stations was in the mountain area. A telegram from Eugene on January 29, 1890, as contained in the United States Signal Service report of 1890, stated: "A very heavy rain has been falling all day and evening; a chinook melting the snows in the mountains all around the heads of the valleys. Indications point to very high water.""

A summary of the 1964 flood is as follows (USGS 1971): "A major storm moved onto the Oregon coast December 18 and brought heavy snow to most of the area. Near-record depths accumulated on the slopes of the Coast and Cascade Ranges and on the floor of the Willamette Valley. On December 20 rapidly rising temperatures, which raised the freezing level to almost 10,000 feet, were accompanied by heavy rains. Frozen-soil conditions, which were caused by extremely cold temperatures December 16 and 17, prevented normal infiltration into the soil, and immediate runoff resulted. The December 19-23 storm brought as much as 15 inches of rain to valley areas and as much as 18 inches to the higher altitudes in the Cascade Range. The heavy rains, supplemented by large quantities of snowmelt, produced floods that have not been equaled in more than 100 years in many parts of the Willamette River basin. (…) Three lives were lost, and more than 210,000 acres of agricultural land was inundated in the Willamette River basin. Flood losses were more than $65 million."

A summary of the 1996 flood is as follows (USACE 1997): "The storm which caused the floods of February 1996 flood began on February 5 and lasted for five days ending February 9. It covered a land area of more than 20,000 square miles centered over the lower reaches of the Columbia River and the city of Portland. (…) Weather conditions in the week prior to the storm were unusually cold, with freezing temperatures over much of the Portland District. Temperatures rose rapidly with the onset of the storm. Mild temperatures during the wettest part of the storm resulted in rainfall at all but the highest elevations of the Cascade Range, a complete melt of all low-elevation snowpack, and substantial melt of mid-elevation snowpack in the Oregon Coast Range and the Oregon Cascades. There was comparatively little melt of mid-elevation snowpack in the

Washington Cascades. The areas hardest hit by the storm were southern Washington and northern Oregon west of the Cascade Divide, including the north Oregon Coast. The central portions of the Willamette and western parts of the Deschutes River Basins were also hard-hit, although less severely. Rainfall amounts were generally unremarkable beyond these areas which bore the brunt of the storm. Within the hard-hit areas, most of the storm rainfall fell in the four-day period from midnight February 4 through midnight February 8. Maximum one-day rainfall amounts were generally not exceptionally severe. However, record-breaking three and five-day rainfall amounts were recorded at many locations. (…) The storm event comprised a combination of record-breaking three- to five-day rainfall over large areas of the Portland District with mild temperatures which produced rainfall up to elevations of 6,000 to 8,000 ft, and substantial snowmelt at low and middle elevations in many areas. Runoff rates were enhanced by frozen ground in the northern part of the Portland District. These conditions led to record streamflows on rivers and streams with tributary basin areas in the order of 100 to 1,000 square miles."

2.5 RESERVOIR REGULATION EFFECTS

Thirteen WVP dams and reservoirs are located on five major tributaries to the Willamette River, regulating about 27 percent of the drainage area of the Willamette River Basin upstream of Portland, and about 41 percent upstream of Salem. Construction on the WVP began in 1940 and completed in 1969. All USACE projects in the Willamette Basins are multi-purpose dams. These functions include flood risk management, power generation, irrigation, water supply, and recreation. Only the features and operations most salient to flood risk management are described here.

Each year has three general reservoir control periods: flood risk management (fall/winter), conservation storage (spring), and conservation holding and release (summer), with the dates of these seasons varying slightly for each reservoir (USACE 2019). A map of the WVP is provided in Figure 2-5, and pertinent data is given in Table 2-1.

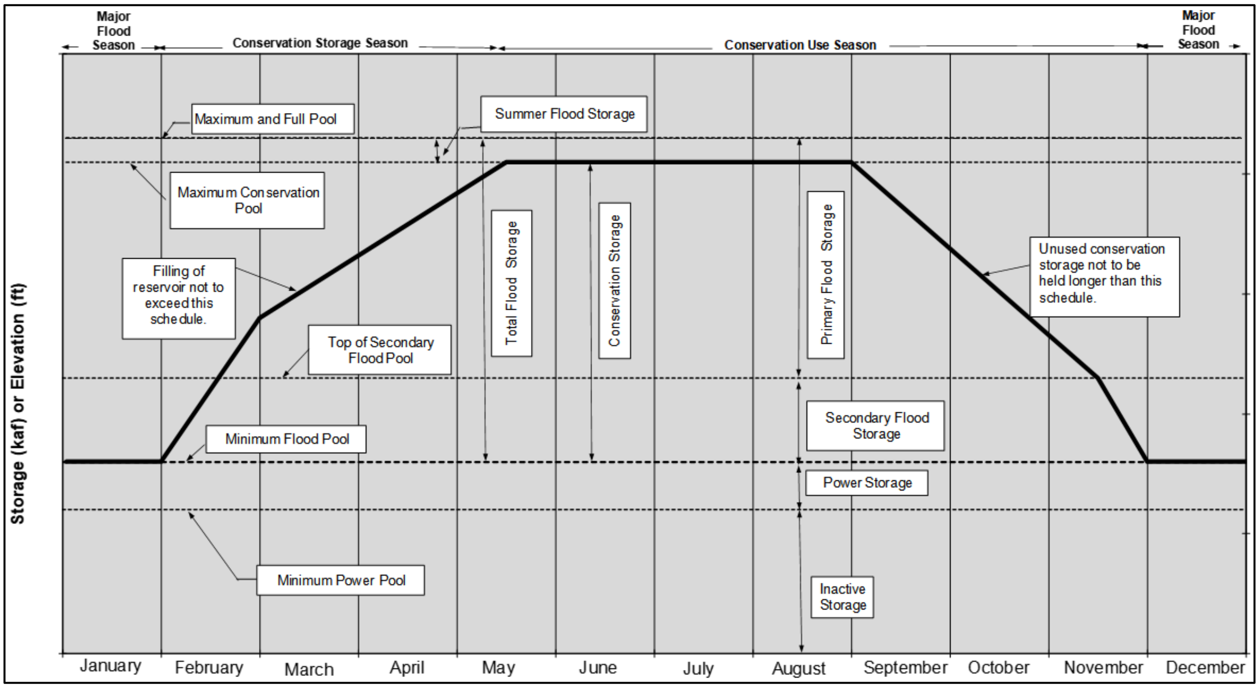
Figure 2-5. Willamette Valley Project overview map

Table 2-1. Pertinent data for reservoirs

Reservoir	Year Construction Began	Year Completed	Conservation storage space (thousand acre-feet)
Hills Creek	1956	1961	195
Lookout Point	1948	1954	325
Dexter	1948	1954	5
Fall Creek	1964	1966	107
Cottage Grove	1940	1942	29
Dorena	1947	1949	65
Blue River	1967	1969	79
Cougar	1959	1963	137
Fern Ridge	1940	1941	95
Detroit	1949	1953	281
Big Cliff	1949	1953	3
Green Peter	1963	1967	250
Foster	1964	1968	25
Total System	**1940**	**1969**	**1,590**

Operation of each project is guided by a water control diagram, including the rule curve, which establishes the elevation at which the pool is to be maintained at or below during various seasons and during seasonal transitions unless regulating a flood event. Figure 2-6 depicts a typical WVP water control diagram, including the rule curve.

Figure 2-6. Typical Willamette Basin project water control diagram and rule curve



Flood storage space is maintained empty during the season when large floods are possible, with refill of conservation space when large floods are becoming less likely and snowmelt is arriving. From September to November or December (depending on the project), the reservoirs are drawn down to minimum flood pool elevations to reserve space to capture and release winter flood flows as necessary. Some time in February (depending on the project), reservoirs can begin to accumulate water in conservation storage (i.e., fill, by releasing less water than flows in). By about the end of May or June, WVP reservoirs are as full as possible for the summer season (USACE 2019).

In addition to the elevation rule curve, the water control plan includes Emergency Spillway Release Diagrams (ESRD) in the flood control zone, maximum and minimum release rates, minimum power releases, and downstream control operations for areas immediately downstream of the dam and further downstream to Salem. The ESRD curves, also known as “special curves”, define minimum required discharge releases based on the reservoir elevation and inflow (or rate of rise).

Average annual runoff is approximately 16 million acre-feet per year as measured at Salem; however, the extremes of annual inflows range from a minimum of approximately 9 million acre-feet (recorded in 1944) to a maximum of approximately 28 million acre-feet (recorded in 1996) as measured at Salem. On average, 7 million acre-feet of runoff occurs between February and May, when projects are refilling. The total conservation system storage in the WVP is 1.59 million acre-feet. While small compared to annual average runoff, this storage is effective in capturing flood flows over short duration atmospheric river events. The water in each reservoir’s conservation pool is emptied each fall in preparation for the flood season, and there are no carryover storage effects from year to year.

House Document 531 (USACE 1948) established the guidelines for flood season operation for the WVP. Two types of flood storage were created. Primary flood storage was designed to provide economically justifiable flood risk management benefits. Primary flood storage allows each reservoir to capture all inflows for all floods of record except the 1861 flood—the largest flood of record. Secondary flood storage was designed with the aim of capturing 90% of the inflow to each reservoir during the 1861 flood. While primary flood storage space was designed exclusively for flood risk management, secondary flood storage was designed to be used jointly for flood risk management and power production purposes. HD531 mandates that secondary flood storage at the non-power projects, as well as primary flood storage, must be evacuated at the start of each flood season. Current practice meets this requirement by evacuating all storage projects to minimum conservation pool before the beginning of the flood season (USACE 2019).

After a flood, evacuation of water for primary storage is accomplished as rapidly as dictated by release schedules specific to each project (typically within seven to 10 days). Water evacuated from secondary storage is generally used for power generation and may be released more slowly. If another flood is imminent, however, releases are made through regulating outlets to evacuate the reservoirs to minimum flood risk management pools (USACE 2019).

USACE is the primary agency with reservoirs operated for FRM in the Willamette Basin. There are other run-of-river dams used for power generation, such as Leaburg and Walterville, but they have negligible effect during floods. Scoggins Dam on Scoggins Creek, a tributary to the Tualatin River, is operated by the Bureau of Reclamation, and flood storage is authorized under Section 7 of the Flood Control Act of 1944. While Scoggins Dam is important for studies of the Tualatin River, it has an insignificant effect on flood flows in the mainstem Willamette River (USACE 2018).

The WVP is operated as a system to reduce flows for communities immediately downstream of the dams, as well as for communities on the mainstem of the Willamette River all the way to Portland, Oregon. The general regulation approach for the system is to operate the dams to reduce flows downstream at multiple control points on the Willamette River and its tributaries. Since most of these dams either have a reregulation dam downstream or operate in series or parallel with nearby dams for the same downstream control point, operations at one dam affects the pool elevation at other dams when operating in the conservation and flood control zones. Above the flood control zone, operations are based on emergency spillway release diagrams for each dam to safely pass the flood. However, system effects are still evident at downstream locations from the variable timing of releases from the upstream dams.

2.6 PREVIOUS STUDIES

While many studies have been undertaken to analyze different parts of the Willamette Basin, there has been no comprehensive study of the entire basin for over 40 years. Many recent studies, such as the Willamette Configuration Operation Plan, Willamette Basin Review, and Draft Willamette EIS, were more focused on conservation season operations and did not include quantitative analysis for flood frequency. Some of the previous studies that included flood frequency curves are summarized below.

1. **1982 analyses**. The last comprehensive study by Portland District that included all areas of the Willamette Basin adopted for use occurred in 1982. Unfortunately, the documentation on this study is scattered. Results are compiled in a binder with loose-leaf pages of plotted flow-frequency curves.
2. **Willamette FIS (USACE 2013)**: The Willamette Flood Insurance Study (FIS) in 2013 was intended to be a comprehensive update to flow-frequency throughout the Willamette Basin. Much of the data preparation and reservoir modeling was positioned to include the whole basin, but the final report only includes flow-frequency curves for the Coast Fork Willamette and Middle Fork Willamette Rivers. These areas were undergoing an FIS update by FEMA, and the values from this report were used as the new effective flood discharges in the updated FIS reports. The hydrology report is known as the Phase 1 report, but there was no Phase 2 report. The methods used were compliant with USACE guidance, but uncertainty was not addressed. A ResSim model was used to develop an unregulated-regulated relationship, which was applied to unregulated flow-frequency curves.
3. **Willamette Flood-Frequency Analysis (USACE 2014)**: In 2014, Portland District undertook a brief study that used an alternate approach to assess flow-frequency throughout the basin. The unregulated frequency curves were largely based on observed USGS records that were available before upstream dams were constructed. For the regulated curves, only data after the construction of upstream reservoirs was used. Either an LPIII distribution or a LOWESS (graphical) curve was drawn through this data. This study was not compliant with USACE guidance. It was meant only to provide contextual information about approximate flow-frequency.
4. **Dam Safety Studies (ongoing**): The Willamette Basin has been the subject of many hydrologic studies for the Dam Safety program under the oversight of the Risk Management Center (RMC). These studies have chiefly been concerned with the dams themselves rather than an assessment of downstream areas. Nearly every project in the Willamette Valley has undergone a Periodic Assessment (PA) or Issue Evaluation Study (IES) in the last 10 years as part of the Dam Safety Program. Within a Periodic Assessment, unregulated inflow volume-frequency curves at the dam site are calculated. However, the level of detail varies from location to location, as the analysis and RMC policy has changed through the years. In addition, some reservoirs were taken to a higher level of study with paleoflood investigations (e.g. Foster and Lookout Point) and greater quantification of historical flood events. While these dam safety studies assessed unregulated inflow volume-frequency and reservoir peak stage-frequency, they did not include the instantaneous peak flow-frequency (either

unregulated or regulated). They were focused on the dam being analyzed and did not include flow-frequency information at downstream locations.

5. **USGS Regional Skew Study (USGS 2020)**: USGS developed regional skew relationships for the entire Columbia River Basin in the report titled "Development of Regional Skew Coefficients for Selected Flood Durations in the Columbia River Basin" (USGS 2020). This study superseded a previous preliminary study done by USGS in 2018 (USGS 2018). Regional skew was a function of only one explanatory variable: mean annual precipitation. The Willamette Basin was included in this analysis, and unregulated volume frequency curves were developed at select locations using no-regulation, no-irrigation (NRNI) data from 1929-2008 without historical information or adjustments. The instantaneous peak duration was not included in this study.
6. **Salem and Willamette Falls (USACE 2020):** As part of the Lower Columbia stage-frequency study, unregulated and regulated volume-frequency curves were calculated at Salem and Willamette Falls. Instantaneous peaks were not included. This analysis was needed to establish boundary condition flows at Willamette Falls for the Lower Columbia and Lower Willamette HEC-RAS model. This analysis was compliant with current USACE guidance, and it relied solely on gaged and estimated flow data. HEC-HMS simulations were attempted using a precipitation-frequency curve using the Willamette PMF HMS model, but the results were highly inconsistent with the flow data, so that attempt was abandoned.

SECTION 3 - ANALYSIS OVERVIEW

A brief overview of the study process is given in this section. There are three major components to the analysis, which are described more fully in the following sections and in the technical appendices:

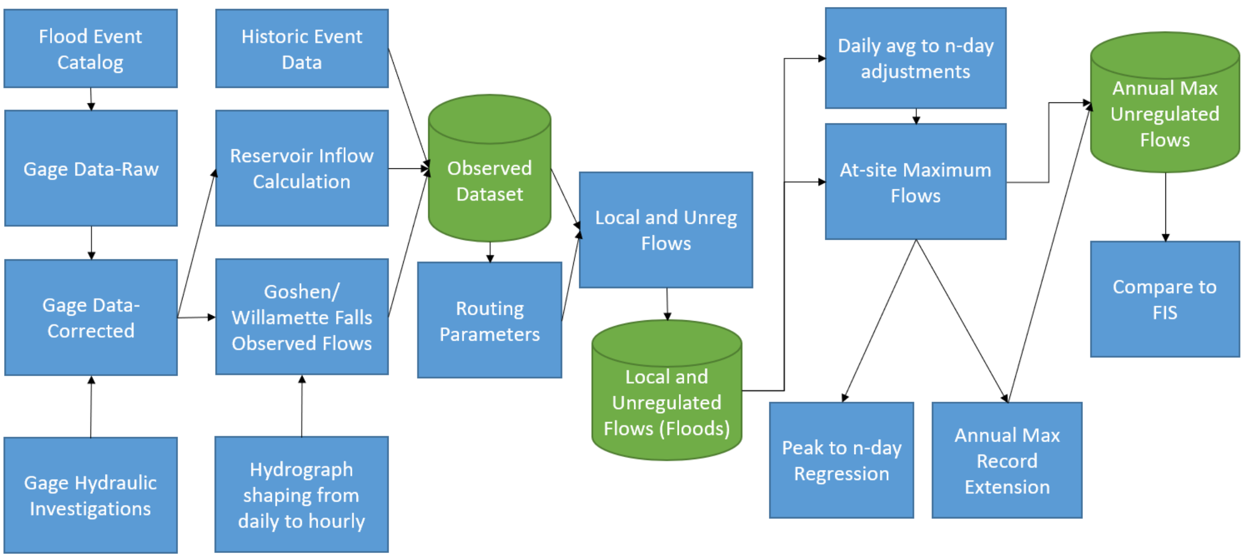
1. **Data Collection and Preparation**. Much effort was placed in retrieving data from source documents, rather than relying on previously compiled datasets used for other studies. This work produced a database of observed flow and stage data only for flood event time windows. A continuous dataset was not produced. Data was collected for annual instantaneous peak, daily average values, and short-interval (hourly) values. This observed data was then used to produce time-series of unregulated flows during flood event time windows. From this data and observed pre-dam records, unregulated annual maximum instantaneous peak and flood volumes over various numbers of days (n-day) were calculated for all study locations. Record extension techniques using nearby gages were used to augment the datasets. The final product of this task was a database of unregulated annual maximum flow estimates at all study locations.
2. **Unregulated frequency curves**. Bulletin 17C procedures were used to calculate unregulated frequency curves for all study locations and durations from instantaneous peak to 15-day. Historic event data and regional skew information were used to improve the estimates. The frequency curves served as the primary basis for estimating probability of a given storm event for which reservoir regulation effects were then applied.
3. **Regulated frequency curves**. An HEC-HMS model was used to generate flood events larger than observed in the period of record by scaling precipitation from historic storms. A HEC-ResSim model was used to simulate reservoir regulation for all inflow events, using pool conditions ranging from completely empty to completely full. After creating this collection of synthetic flood events, a Monte Carlo process was used to generate regulated flow-frequency estimates.

SECTION 4 - DATA COLLECTION AND PREPARATION

Reliable datasets are foundational to any hydrologic study. The most cutting-edge analysis techniques are wasted if the input data to the analysis has not been thoroughly reviewed. Quality control processes were used at many points throughout the data preparation process.

Appendix A contains detailed information on the data collection and preparation in this study. A summary of the methods is provided in this section. Figure 4-1 shows a flowchart of the data collection and preparation process. The key activities are summarized below:

Figure 4-1. Flowchart of data collection and preparation



1. **Flood Event Catalog**. Flood event time windows were identified where short time step data collection and quality control (QC) was be prioritized from 1929-2021, when most gage data is available. Existing unregulated daily flow datasets were used to identify the time windows. A primary flood window was identified for each year based on records at Salem. In some years, secondary flood windows were identified that had higher flows at other parts of the basin.
2. **Data Collection**. The data collection effort for this study was extensive, since such a large geographic area is covered for as far back as historic records allow. Digital databases were mined, and significant effort was placed into digitizing information from paper files.
3. **Data Corrections**. A robust QC process was followed for the gage data, and other QC processes in subsequent steps also revealed issues that were remedied.

4. **Historic Event Data**. While streamflow gage records provide much information about past flood events, there is usually additional information about past floods from other sources that can inform a flood frequency analysis. Post-flood reports, design documentation, USGS publications, and other sources were researched to find information on historic floods.
5. **Reservoir Inflow Calculation**. Inflows to reservoirs are usually calculated values based on known reservoir outflows and change in storage. This calculation of project inflow is performed automatically in the USACE Corps Water Management System (CWMS) database as data is collected in real-time. These records are termed “observed” inflows here. In some cases, the observed inflows from CWMS appeared questionable. In this study, the corrected reservoir outflow and elevation were used to re-calculate inflows over the period of available data. After re-calculating inflows for all reservoirs, a judgment was made on whether to use the “observed” inflows from CWMS or use the re-calculated inflows for each event based on how realistic the hydrograph visually appeared.
6. **Reconstructed Observed Flows at Goshen and Willamette Falls.** The USGS gage on the Coast Fork Willamette River at Goshen was not operational between water years 1913-1950. For water years 1924-1951, a gage was operated upstream at Saginaw. For WY 1941-1950, the Saginaw gage records were used to reconstruct the observed flows at Goshen. While extensive stage records are available at Willamette Falls, corresponding discharge values are not available. USGS has not developed a rating curve at this location due to the close proximity to control structures on Willamette Falls, such as the T.W. Sullivan power plant. Flows at Willamette Falls were estimated by applying hydrologic routing techniques, using the upstream gage records at Salem and adding in the intervening tributaries.
7. **Gage Hydraulic Investigations.** Coordination with USGS was undertaken to verify the peak flow estimates included all flow inside channels and overbanks, not just the main channel. For instance, on the Coast Fork Willamette at Goshen gage (14157500), the gage location is near a bridge. At extreme high flows, such as the December 1964 event, water can take alternate flow paths that skirt the main channel. Coordination with USGS personnel about this potential revealed that peak flow estimates for situations like this include the main channel and overflow side channels as well.
8. **Routing Parameter Development**. A new set of hydrologic routings were developed for this study. These routing parameters were applied consistently in unregulated flow calculations, HEC-HMS modeling, and HEC-ResSim reservoir modeling. Modified Puls or the standard Muskingum routing scheme were used for all reaches, replacing the legacy streamflow synthesis and reservoir regulation (SSARR) routings. Refer to Appendix C for the routing parameter development and calibration.
9. **Hydrograph Shaping from Daily Average Data**. For older records, often the only information readily available is daily average data, with an estimate of the

annual maximum instantaneous peak. For flood routing studies, a daily average timestep is often inadequate, and a hydrograph with more definition is needed. A method was developed to generate hourly hydrographs from daily average and annual maximum data using a cubic spline interpolation approach. Any approach to solve this issue will have drawbacks and errors associated with it, but applying the method proposed here results in a more realistic hydrograph than if no modification were to be done.

10. **Local and Unregulated Flow Hydrographs.** Local flows are the difference between the observed, gaged flow at a location and the theoretical flow routed from upstream points. Local flows were calculated for all periods where valid hourly observed data existed. The local flows were then combined and routed downstream to produce unregulated flow hydrographs. The unregulated flow hydrographs were only produced for periods of time with valid observed data.
11. **Daily average to n-day adjustment**. Daily average data is typically averaged from midnight to midnight, local time. When performing a volume-frequency analysis, using daily average data to compute flood volumes will systematically underestimate the actual flood volumes. This effect is largest for shorter durations, such as 1-day, and becomes less important with longer durations. To account for this systemic bias, hydrograph shaping techniques were used to generate hourly hydrographs. N-day volumes were then extracted from these shaped hydrographs, which resulted in nearly unbiased estimates of the mean and variance of these records.
12. **At-site maximum flows**. Data from multiple sources was merged to produce a single database of unregulated flows for each location. Data was combined from at-site hourly unregulated flows, pre-regulation observed flows, drainage area ratio extensions from very nearby sites on the same river, historic records, and estimated adjustments to observed flows based on the cumulative change in upstream reservoir storage.
13. **Peak to n-day regressions**. For many historic events, only instantaneous peak data is available without daily average flow estimates. To estimate n-day volumes from a given instantaneous peak estimate, regression relationships were developed for each location using unregulated data from sites that have hourly data.
14. **Annual Maximum Record Extensions**. Flow records at nearby gages with long-term records were used to extend the record at each study location. MOVE.3 (Maintenance of Variance Extension) procedures described in Bulletin 17C were used to perform record extension.
15. **FIS Comparison.** After compiling the extended annual maximum unregulated dataset, it was compared to the previous basin-wide unregulated dataset from the Willamette FIS (USACE 2013). Despite the different analysis techniques, the results from the current study were similar to the previous Willamette FIS dataset at all locations and durations.

SECTION 5 - UNREGULATED VOLUME-FREQUENCY ANALYSIS

Annual flood volume frequency curves provide the chance that flood runoff will exceed a given value over a specified duration in any given year. A family of annual volume frequency curves for multiple durations are sometimes known as Volume-Duration-Frequency (VDF) curves. Volume frequency analysis is performed on datasets reflecting natural conditions with all upstream storage effects removed (unregulated). In this report, unregulated annual flood volume frequency curves are typically expressed as “volume frequency curves” for convenience. Runoff volumes are expressed as average flows over a given duration rather than in units of volume so that the results for different durations can be easily compared on a common plot axis. These curves do not show the probability of flood flows under current-day reservoir conditions and should not be used directly as an estimate of flood risk experienced by downstream communities. These curves are a necessary starting point to explore the effects of upstream reservoirs, discussed in Section 6.

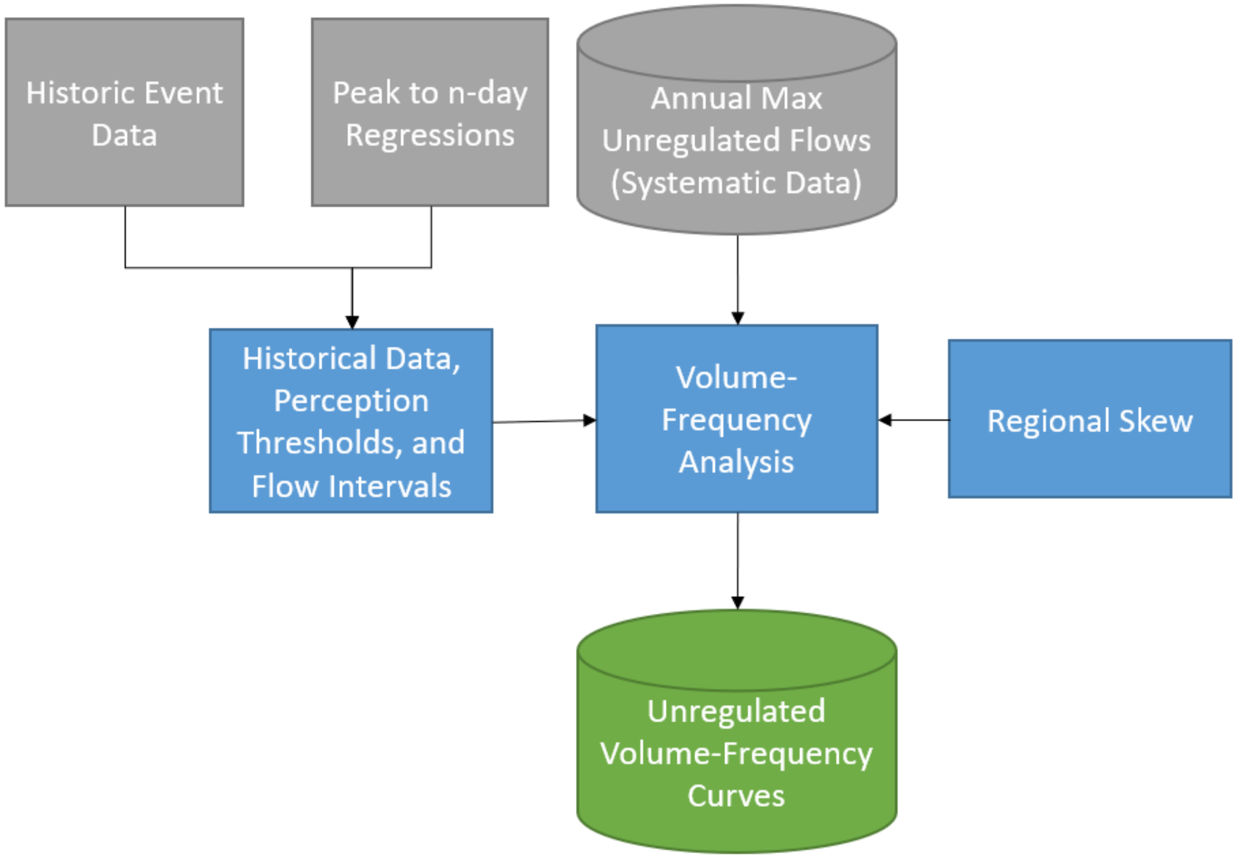
Appendix B details the development of unregulated flood volume frequency curves at all study locations for durations from instantaneous peak to 15 days. The results were then used as inputs to the regulated flow-frequency analysis. A summary of the process is presented here.

5.1 STUDY APPROACH

Figure 5-1 shows a flowchart of the process used to calculate unregulated volume-frequency curves. The use of an HEC-HMS model was considered to help inform the frequency analysis, but it was ultimately not pursued, largely because the model results compared poorly to observed flows.

The potential presence of mixed populations in the Willamette Basin was investigated to determine if splitting the flow record by flood-producing mechanism was justified. Two potential driving flooding modes are snowmelt and rainstorms generated by atmospheric rivers. Convective events (i.e. thunderstorms) are not common in the Willamette Basin, and when they do occur, flows are far lower than atmospheric river flood events (NOAA 1994). All significant flood flow events in the winter were sourced from atmospheric rivers, as evidenced by conversations with reservoir regulators and forecasters, review of post-flood reports, and other academic papers (Harr 1981, USACE 1966, USACE 1997, Barth et al. 2017, Corringham et al. 2019). Since the flood-producing mechanism was nearly always an atmospheric river event, annual maxima data was used without subdividing by season or flood mechanism. The large majority of annual maxima were between November and March, though some atmospheric river events that occurred just outside these months were also included. Refer to Appendix B for more discussion.

Figure 5-1. Flowchart of unregulated volume-frequency analysis



5.2 SYSTEMATIC DATA

Per Bulletin 17C, systematic data is “collected at regular, prescribed intervals under a defined protocol. In the context of streamflow, systematic data consist of discharge and stage data collected at regular, prescribed intervals, typically at streamflow-gaging stations.” In this study, systematic data was annual maximum unregulated records at each study location. Systematic data was sourced directly from Appendix A. The systematic data includes both at-site data and data sourced from record extensions with nearby sites using the MOVE.3 technique.

5.3 HISTORICAL DATA

Bulletin 17C encourages the analyst to include information from all past known floods outside the period of systematic data. These historic events are often represented as flow intervals with a lower and upper bound, rather than a single known discharge value, to account for the uncertainty in these estimates. Historical data was included for all locations and durations.

Rather than using the estimates from design documents directly, the 1861 flood estimates were revisited in this study using regression approaches. The 1861 estimates were then applied to the frequency analyses as flow intervals to include the considerable uncertainty in these estimates. The only reliable flow estimates for this event are the peak flows at Salem, Albany, and Jefferson. For each study location, a linear regression was developed relating the peak at one of these 3 sites with the peak and n-day volumes at the study location. Of the three candidate locations, the one with the highest correlation to a given study location was used. From these regressions, a best estimate, lower bound, and upper bound were calculated for the 1861 flood. A 95% prediction interval was used to generate the upper and lower bounds.

While December 1861 is the most well-known flood in the 19th century, other, earlier, major floods also occurred. For 5 floods between 1813 and 1853, estimates of stage at Salem were available. These estimates were sourced from very limited information from personal journals and newspaper articles. The evidence showed that these events were much larger than average, but not quite as large as the 1890 event. The same regression approach was used to estimate flow intervals for these events at study locations based on instantaneous peak flow at Salem.

Two paleoflood analyses to identify floods from geologic information were available for the Willamette Basin: one at Lookout Point, and one at Foster (USACE 2018, USACE 2022b). The paleoflood results were not used in this study for the following reasons:

1. There is considerable uncertainty in the paleoflood estimates of peak flow and date. This is inherent to any paleoflood study in a dynamic geomorphic environment like the Willamette Basin.
2. The paleoflood study results are relatively inconsistent with the probable maximum flood estimates.
3. The paleoflood results are only available at two locations. These results would need to be extended to other study locations to ensure consistency in the volume frequency curves between locations.
4. A more comprehensive paleoflood study of more locations throughout the Willamette Basin is underway.
5. Paleoflood estimates typically are most useful to inform very extreme probabilities of interest for dam safety applications.

If a more comprehensive paleoflood study of the Willamette Basin is completed in the future, it could be incorporated into an updated version of this flow-frequency study.

5.4 PERCEPTION THRESHOLDS

Per Bulletin 17C, perception thresholds represent the “observable range” of floods. Most commonly, perception thresholds are used to describe the knowledge that floods were below a given value over a range of years. The lower perception threshold represents the smallest peak flow that would be detected for a given year, based on physical indicators and written record availability. This concept implies that if an event larger than the lower perception threshold had occurred, a record would have been kept and documented. It also implies that in years that a record was not made, the peak flow was below the threshold. In this study, three general periods with different perception thresholds were used: 1813-1861, 1862-1890, and 1890-present.

5.5 REGIONAL SKEW

Bulletin 17C recommends that the adopted skew coefficient be the weighted average of the station skew and a regional skew to leverage information from nearby sites. Regional skew for the instantaneous peak was sourced from the 2005 skew study (USGS 2005), and regional skew for the 1-day, 3-day, 7-day, 10-day, and 15-day durations was sourced from the 2020 study (USGS 2020).

Willamette Falls, Salem, and Albany have very large drainage areas compared to the other study sites. The regional skew studies did not include sites similar in character to these sites, and the systematic plus historical period is very long for these sites. Therefore, regional skew was not applied for these sites. Instead, only station skew was used. However, had the regional skew been applied, its impact would have been small due to weighting proportional to the equivalent (and actual) record length.

5.6 VOLUME-FREQUENCY ANALYSIS

Flood frequencies are commonly determined using stream gage data and procedures described in Bulletin 17C (England et al 2019). The Bulletin 17C methodology estimates the recommended Log-Pearson Type III (LP3) distribution parameters from the moments of the sample data (i.e. mean, standard deviation, and skew) using the Expected Moments Algorithm (EMA). The multiple Grubbs-Beck test is used to account for potentially influential low flows (PILFs). While the 17C guidance is intended for instantaneous flows, it is also applicable for volume frequency analysis.

Bayesian approaches are gaining in popularity, and software such as RMC-BestFit is lowering the barrier to entry for these methods. However, the results from this study are intended to be applicable for future FEMA hydrology studies. Bulletin 17C remains the federal guidance adopted by FEMA, so Bayesian approaches were not pursued in this study.

5.7 RESULTS

A computed flow frequency curve is only an estimate of the probability distribution of the parent population. Confidence intervals can be used to provide a measure of the uncertainty of the estimated exceedance probability of a selected discharge or a measure of the uncertainty of the discharge at a selected exceedance probability. The standard 90% confidence interval (i.e. the 5% and 95% percentiles) was calculated in this analysis to represent curve uncertainty.

The confidence limits of the LPIII distribution are defined as part of EMA, and they are influenced by the standard deviation of data (influenced by defined flow interval values), sample size, and censoring threshold. The confidence limits direct from EMA should be used if the curve is used for at-site studies. However, if the volume-frequency curves are intended to be sampled in a Monte Carlo simulation via bootstrapping, the confidence limits from EMA cannot be used directly. When applying bootstrapping sampling, a single parameter is used to characterize uncertainty with an LPIII distribution: the effective record length (ERL). Higher effective record lengths yield narrower confidence limits. In this study, most ERLs are between 100 and 150 years.

Complete results are provided in Appendix B. A series of sensitivity analyses were performed to better understand the effect of key inputs on the results, including varying the historical flood estimates, regional skew, and perception thresholds. Comparisons to previous studies were also explored.

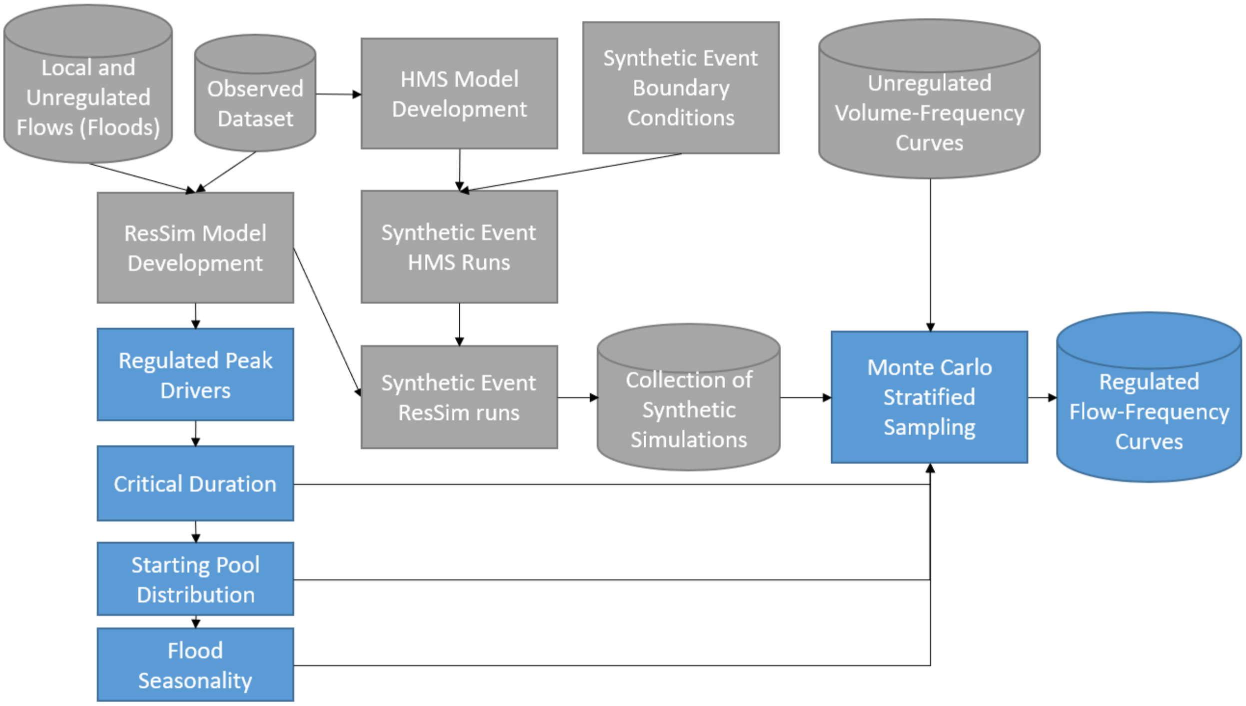
SECTION 6 - REGULATED FLOW-FREQUENCY ANALYSIS

The previous section explored the probabilities of flood flows throughout the basin under a more natural condition without upstream reservoirs. This section explains how upstream reservoir effects were added to the analysis to develop regulated flow-frequency curves. These curves show the chance of river flows rising above a level of interest in any given year, including current flood risk management operating policies. These curves are appropriate for communicating flood risk to communities for floodplain management and emergency action planning. These results have uncertainty associated with them that should be clearly stated and understood when using the results.

6.1 STUDY APPROACH

An overview of the methods used in the regulated flow-frequency analysis is given in this section, with details on the tasks in the following sections. For a more detailed discussion, refer to Appendix G. Regulated flow-frequency curves are a function of many different inputs, including the storm event magnitude, duration of the event, distribution in space, distribution through time, the time of year, reservoir operational policies, and the starting pool conditions at the onset of the event, to name a few. Since there are so many related variables that affect the results, there is no simple analytical solution. In these situations, Monte Carlo techniques perform simulations of many flood events, accounting for the probability of each of the various inputs. Figure 6-1 shows a flowchart of the process used to calculate regulated flow-frequency curves.

Figure 6-1. Flowchart of regulated flow-frequency analysis



A classical approach to developing regulated flow frequency curves is to develop an unregulated flow-frequency curve and apply an unregulated-regulated relationship. This approach is detailed in EM 1110-2-1415 (USACE 1993). While attractive for its simplicity, this approach has some drawbacks for this study application. Most notably, the effect of reservoir operations is distilled down to single transformation. At the 1% AEP event, it is assumed that the reservoir system will decrease flows from the unregulated condition by a single amount. While uncertainty in the unregulated-regulated relationship can be considered, the impact is usually an increase in the uncertainty bounds, rather than affecting the best estimate of the 1% AEP event. In reality, regulation of an unregulated 1% AEP event depends greatly on the starting pool condition, which is implicitly assumed in the unregulated-regulated relationship. It also depends on the shape of the flood hydrograph, the distribution of volume around the basin and other factors. It is difficult to evaluate alternative reservoir operation policies using this approach, since sometimes the differences in regulated peak flows occur for different events than the limited set used to build the unregulated-regulated relationship.

In addition, an unregulated-regulated relationship assumes that the 1% AEP regulated event corresponds with the 1% AEP unregulated event. As discussed in Appendix G, this is not often the case for a reservoir system like the Willamette where the flood storage space varies seasonally. The 1% AEP regulated event is often sourced from inflow events more common than the 1% AEP unregulated event that occur at times when reservoirs have limited storage space available to manage flooding. For these reasons, an unregulated-regulated curve approach is not suitable for this study, and Monte Carlo approaches were used instead.

In a traditional Monte Carlo simulation approach, input variables (either precipitation or flow volume) are randomly sampled many times, and hydrologic models like HEC-HMS and HEC-ResSim are simulated many times within the Monte Carlo sampling loop. Under this approach, the models constitute most of the compute time, and there are often many simulations that are nearly duplicated. A flowchart showing this type of Monte Carlo simulation process is shown in Figure 6-2. HEC-WAT and RMC-RFA use this approach.

The approach taken in this study uses a variation that greatly reduces run time. Many HEC-HMS and HEC-ResSim simulations with various inflow shapes and starting pool conditions were performed to generate a response surface before any Monte Carlo techniques were used. For the flow-frequency analysis, the common collection of events was processed separately for each study location. The approach is analogous to a coincidence analysis, with event volume over the critical duration as variable A, starting pool as variable B, and the peak regulated flow as the response variable C. To perform the coincidence analysis, Monte Carlo techniques were used, since the total probability method coincident frequency analysis in HEC-SSP cannot fully account for uncertainty or variations in event shape for the same event volume. The primary benefit of this approach is that the HEC-HMS and HEC-ResSim models only needed to be run one time. If an alternate input probability distribution was used (e.g. starting pool distribution), the HEC-HMS and HEC-ResSim models did not need to be run again. A flowchart of the approach used in this study is shown in Figure 6-3.

Figure 6-2. Traditional Monte Carlo process for regulated flow frequency

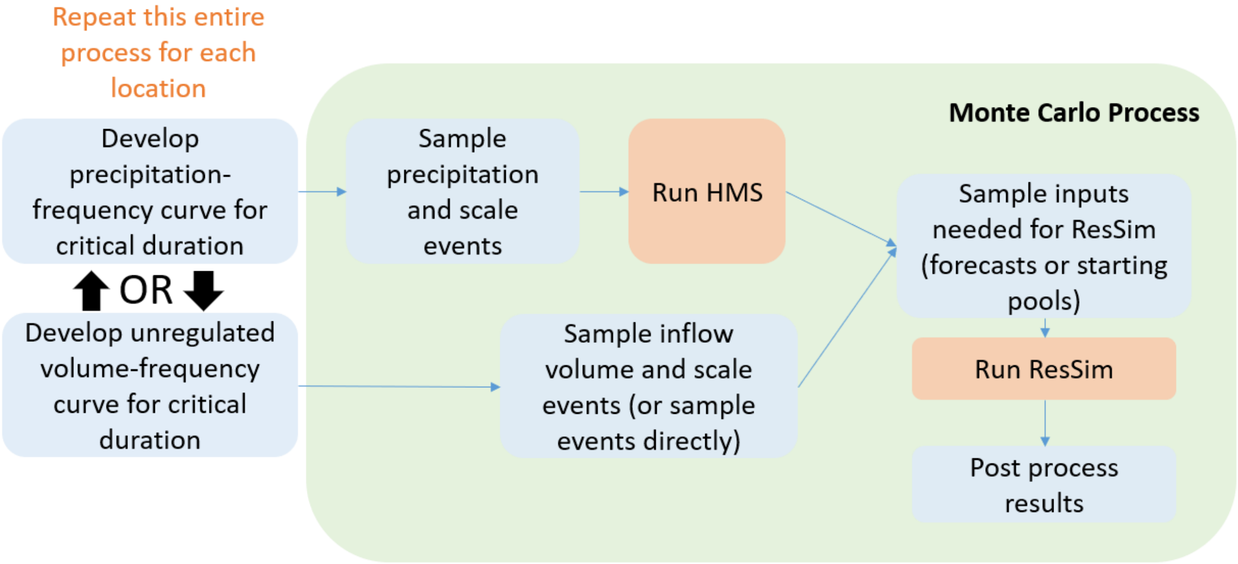
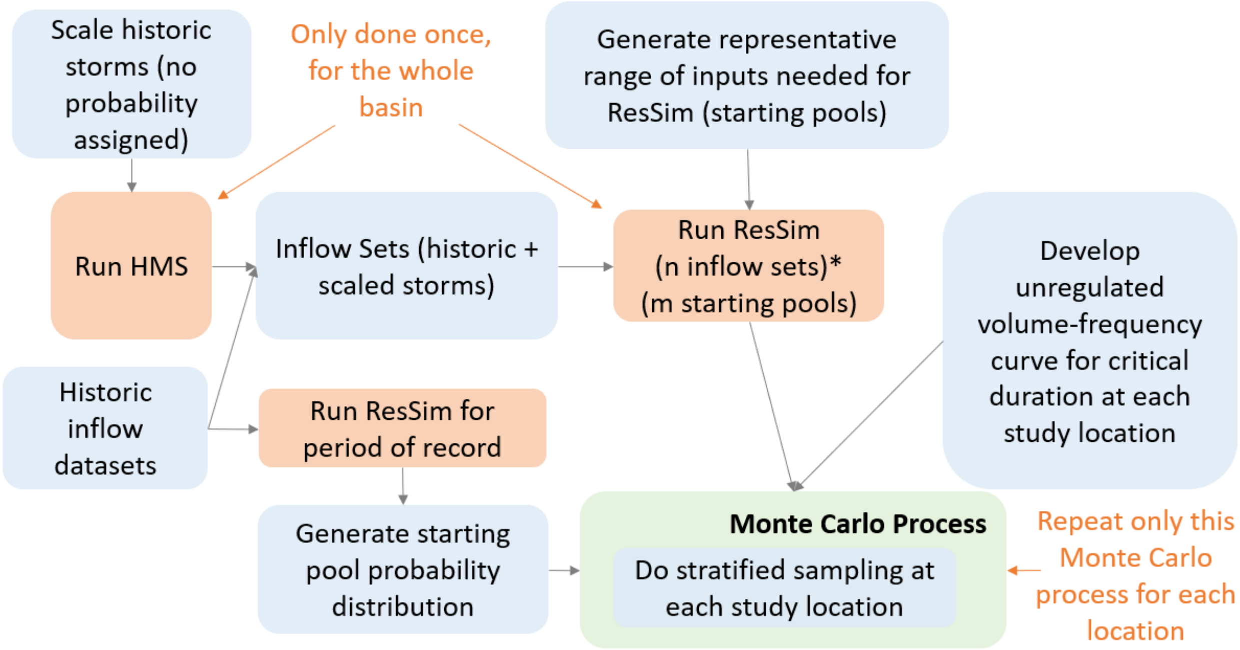


Figure 6-3. Current study Monte Carlo process for regulated flow frequency



6.2 HEC-HMS MODEL DEVELOPMENT

Appendix D details the development of the HEC-HMS model, which simulates rainfall-runoff processes. The HEC-HMS model updated the existing CWMS model and focused the model parameterization on flood events of interest for the study. Additional calibration events were simulated, and the subbasin delineation was adjusted to meet the needs of the study. Snowmelt parameters were updated. A period of record simulation was performed using an hourly dataset extending from 1929-2017, sourced from Weather Research and Forecasting (WRF) inputs. Simulations using WRF data normalized to daily average PRISM precipitation amounts produced more reliable results for the years after 1981 when PRISM data was available.

6.3 HEC-RESSIM MODEL DEVELOPMENT

Appendix E details the development of the HEC-ResSim model, which simulates reservoir operations. Existing ResSim models from previous studies were combined to produce a new model tailored to the purposes of the study. The model was focused on simulating flood events accurately, but it also produced reasonable results for the conservation season. The model was calibrated to six events for flood operations and three water years for the conservation season. The ResSim model cannot fully replicate real-time decision making, so model uncertainty was analyzed.

The ResSim operational alternative primarily used in this study is termed the “FRM Baseline.” This alternative is used to represent operations considered reliable or dependable for FRM purposes. It does not include operations that provide an incidental FRM benefit, since these may change through time. The FRM Baseline alternative is intended to conform with EM 1110-2-1415, which states that operations for project purposes other than FRM may provide incidental storage space, but the effect of this space on FRM should be estimated very conservatively.

6.4 SYNTHETIC FLOOD SIMULATIONS

Appendix F details the development of synthetic flood events. Since only a few extreme flood events are available in the historic record, synthetic floods were generated to produce new storm patterns and starting pool conditions that stress the reservoir system in different ways. For ten historic flood events, precipitation was scaled up using multipliers between 1 and 3 and simulated in HEC-HMS. A factor of 3 is the maximum multiplier per EM 1110-2-1415, and the largest scalings are similar to probable maximum precipitation amounts at some locations. Each basin-wide set of inflows for a flood event was simulated multiple times in ResSim, using different starting pool conditions. Quality control was an important step in the process, and data corrections were made to ensure consistent simulation results.

Synthetic events were produced for individual flood events, not for the whole water year. The synthetic events here were not designed to correspond to specific annual exceedance probabilities (AEP). Rather, the purpose of this work was to create many plausible synthetic floods that covered a wide probability range. 22,185 synthetic simulations of basin-wide regulated flow were computed for this study.

6.5 MONTE CARLO TECHNIQUES

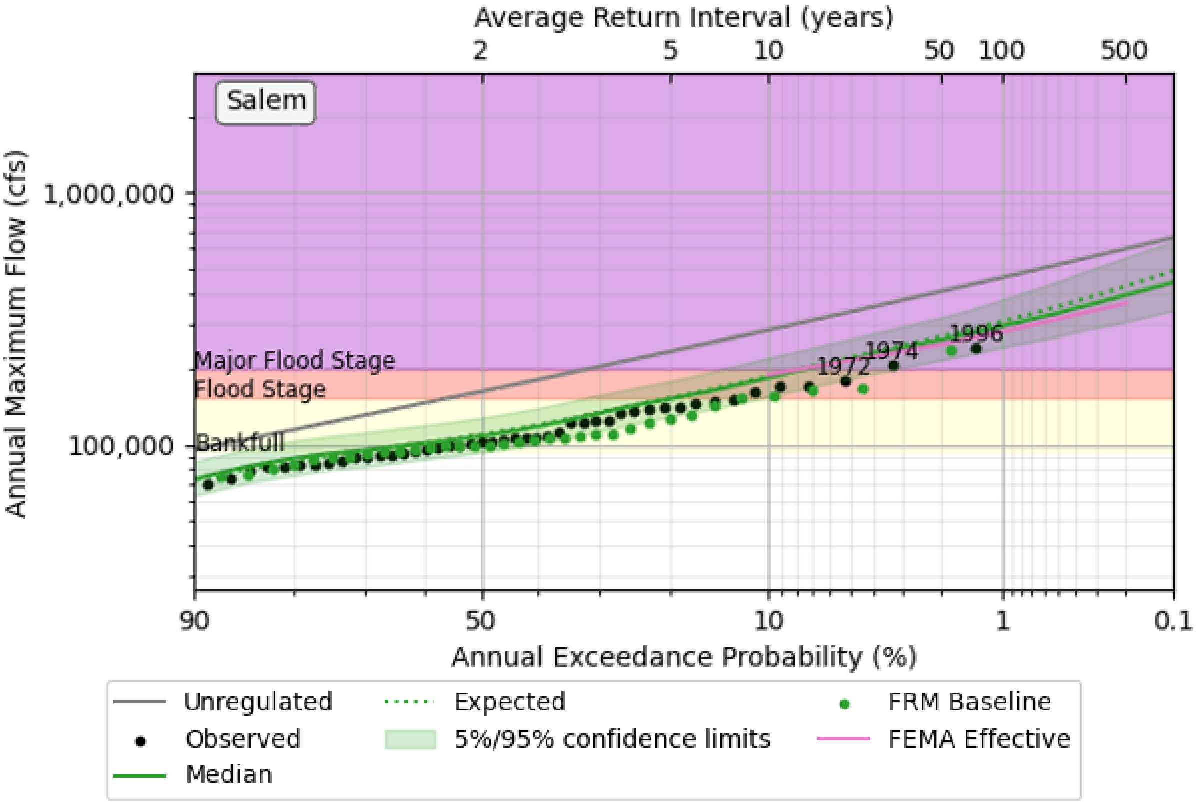
Appendix G details the Monte Carlo techniques used to generate regulated flow-frequency curves. Inputs to the process included unregulated volume-frequency curves, critical duration, starting pool distributions, date of peak flow distributions, and the collection of synthetic events. A stratified sampling approach was used, which provides better definition on the extreme end of the flow-frequency curve than a standard (or naïve) Monte Carlo approach. Since the adopted frequency curves are a composite of many different types of events sampled in the Monte Carlo process, there is no single event that corresponds to a given AEP. Diagnostic information is provided that discusses the general types of events that drive the 10%, 1%, and 0.1% AEP events.

6.6 RESULTS

Regulated flow-frequency results are provided for the median curve, expected curve, and 5% and 95% confidence limits (90% confidence interval). Figure 6-4 gives an example of the results. Complete results are provided in Attachment 5 of Appendix G. The adopted median regulated flow-frequency curve is shown as a solid green line, with the shaded area representing the 5% and 95% confidence limits (90% confidence interval). The dotted green line shows the adopted expected curve. The green lines and shaded area were produced by the Monte Carlo techniques detailed in Appendix G. The figures also contain reference information for context. The regulated flow-frequency from the currently effective FEMA Flood Insurance Study is shown as a pink line. The unregulated peak flow-frequency curve from Appendix B is shown as a solid gray line. Individual points are plotted in black for the observed USGS annual peak data for all years after upstream regulation was complete, using median plotting positions. Similarly, points are plotted for the simulated HEC-ResSim model output in green, though this only includes the years from 1981-2019.

A series of sensitivity analyses were performed to better understand the effect of key inputs on the results, including varying the critical duration, date of peak distribution, starting pool distribution, and reservoir operational policy. The results were compared to observed data and existing regulated flow-frequency curves from FEMA studies. The results show the reservoirs substantially reduce peak flows throughout the basin compared to a natural condition, even at the 0.1% AEP event.

Figure 6-4. Example of regulated flow-frequency results



SECTION 7 - CLIMATE CHANGE

A qualitative analysis of the potential impacts of climate change was performed for this feasibility study per the guidance in ECB 2018-14 (USACE 2018), ER 1100-2-8162 (USACE 2013), and ETL 1100-2-1 (USACE 2014). This is a study of existing conditions without any proposed actions, so only the future without-project condition is discussed (i.e. the No Action Alternative). Per ECB 2018-14, sea level change analysis is not required because the study area is above 50 feet NAVD88. The study area is upstream of Willamette Falls, which acts as a hydraulic control. Many climate assessments have already been performed for the Willamette River Basin, which are summarized here.

Allgeier (2019) evaluated naturalized flows at Salem from 1929-2008, with reservoir regulation and irrigation effects removed. In the analysis of unregulated flows, only 1 uncorroborated nonstationarity was detected. Because this single nonstationarity in 1984 did not exhibit either consensus or robustness, it was considered as not genuine, and the naturalized annual peak flow dataset was treated as homogenous across the period of record.

A pair of recent River Management Joint Operating Committee (RMJOC) reports describe the effects of climate change. The unregulated condition is in Part 1 (RMJOC-II 2018), and the regulated condition is in Part 2 (RMJOC-II 2020). Key conclusions from these studies related to flood risk in the Willamette are summarized below:

- Future precipitation trends are uncertain, but a general upward trend is likely for the rest of the 21st century, particularly in the winter months.
- Average winter snowpacks are very likely to decline over time as more winter precipitation falls as rain instead of snow.
- By the 2030s, higher average fall and winter flows, earlier peak spring runoff, and longer periods of low summer flows are very likely.
- In the Willamette Basin, fall and winter flows are likely to increase.
- Identified shifts in runoff volume timing and variability in the spring could stress the reservoir system.
- The greatest identified change in future flood risk is from increased winter flood volumes throughout the Columbia Basin. Increases in inflow are projected from the Willamette River during winter events.
- The current system operations for flood risk management (FRM) are not designed for the projected future hydroclimate of the basin. However, while changes to reservoir operating policies via adaptive management may partially ameliorate the climate effects, changes to operations are not anticipated to fully offset potential increases in flood risk.

A climate assessment has also been performed as part of the Draft Willamette Environmental Impact Statement (USACE 2022c). The findings from that assessment are similar to the conclusions of the RMJOC work. The summary of the projected trends in climate is provided below:

- Wintertime precipitation and streamflows are anticipated to increase over historical norms. This projection emphasizes the continued need for reservoirs to function as flood risk management projects into the future. The associated increases in reservoir inflow may lead to more frequent high pool events and prolonged periods of flood operation in the winter and spring seasons.

- Summertime streamflows are consistently projected to decrease in the future relative to historical norms. There is strong consensus for this trend across the spectrum of climate model scenarios and within existing literature. This indicates that while reservoirs may be tasked to serve an increasing role in flood risk management, they may also be stressed in the summertime months to supply adequate quantities of water for irrigation, water supply, and required ecologic minimum flows.

- The seasonal timing of the transition from higher wintertime flows to lower summertime flows is not adequately addressed in the literature. This timing is of particular importance to anticipating required changes in reservoir operation.

- Projected future temperatures are anticipated to increase significantly over historic norms. This has various hydrologic implications including increased atmospheric moisture, evapotranspiration rates, frequency of wildfires, hydropower demand, and water supply demand.

SECTION 8 - FURTHER WORK

While this study achieved the project purpose, there are opportunities for improvement in the future. A few potential items that could be pursued further are listed below:

- **Routing Techniques**. This study used hydrologic routing techniques, which showed adequate performance. However, direct application of hydraulic models could produce more reliable streamflow routing. The primary barrier to this is the increased complexity introduced with detailed hydraulic models and the large increase in simulation compute time. Alternately, the hydrologic routing parameters could be improved if the hydraulic models used to generate these parameters were enhanced by incorporating higher-quality bathymetry and additional calibration events.

- **Regional Skew**. The regional skew values for the 1-day and longer durations are from a recent study in 2020. However, the regional skew for instantaneous peaks is from a different study from 2016. An updated skew study that used the same methods and data sources as the 2020 study could produce more consistent results between durations.

- **Additional synthetic floods**. The study scaled precipitation from 10 historic storms to produce floods larger than observed in the period of record. While these scaled events were valuable additions, more synthetic events would enrich the dataset further. A stochastic weather generator could be used to produce additional extreme floods.

- **Stage-Frequency**. This study produced flow-frequency curves at 24 discrete locations. Hydraulic models could be used to better estimate the rating curve with associated uncertainty at extreme events. These rating curves could then be used to estimate stage-frequency curves.

- **Additional Locations**. Results are provided at 24 locations, but there are other locations where updated flow-frequency curves would be of interest. Additional locations could be added to the study to provide more resolution.

- **Inundation Mapping**. Inundation mapping was not included as part of this study. Before producing detailed inundation maps, additional flow inputs for tributaries and creeks would need to be developed beyond the study locations in this study.

- **Reservoir Operation Changes**. This study only included current operating policies of the Willamette Valley Project. If alternate operating plans are considered in the future, this study provides a roadmap in Appendix G for evaluating the effect on FRM of these changes to operations.

SECTION 9 - CONCLUSIONS

Some general conclusions from the study are summarized below:

- **The uncertainty in the unregulated frequency estimates is dominated by the limited period of record of flood events.** Hydrologic uncertainty from a limited period of record was the largest variable impacting the certainty of results. Since observed data is available only for around 150 years, there is relatively low confidence in estimates of extreme floods.
- **Reservoir regulation has significantly reduced the chance of flooding**. This is not a new finding, but this study revisited the quantitative analysis. It confirmed that the upstream system of reservoirs is effective in reducing even very large floods. For example, the system of reservoirs has lowered the likelihood of reaching major flood stage at Salem in any given year from approximately 33% (1 in 3) to 7% (1 in 14). Even at an extreme 0.1% AEP (1000-year) flow, the reservoirs still provide an appreciable reduction in peak flows at all locations.
- **Changes in reservoir operations have not increased flood risk**. While there have been changes to reservoir operations policies for ecosystem purposes and Endangered Species Act compliance, these operational changes have not increased flood risk. This outcome was expected, since the operational changes were formulated to avoid flood risk increases. The study approach easily allows future proposed operational changes to be evaluated and compared.
- **Damaging floods can occur many different ways.** Damaging floods can be produced by different mechanisms, such as a single extremely large winter storm when pool levels are low, a series of back-to-back events, or a smaller storm that occurs in the spring when reservoir levels are high. The dominant flooding mechanism varied by location and flood level. The recent April 2019 flood was a reminder that damaging floods are not limited to winter months.
- **The uncertainty in the regulated frequency estimates is a mix of model error and hydrologic uncertainty.** At common events, like the 50% AEP (2-year), the uncertainty in the estimate is dominated by model error, reflecting the inability of models to replicate real-time decisions. At rare events, like the 0.1% AEP (1000-year), the model error term is largely overwhelmed by hydrologic uncertainty from a limited period of record of observations. The probability of inflow events at these high levels is very uncertain.
- **The regulated flow-frequency curves from this study generally are lower than previous studies**. At most locations, the 1% AEP (100-year) event flow is lower in the current study than in previous FEMA effective studies. There are some exceptions, most notably at Blue River, Foster, and Salem. It is challenging to attribute the cause of these differences due to sparse documentation of the previous studies. The previous studies may have been more conservative, leading to higher estimates.

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